The Role of Emerging Technologies in Improving Energy Efficiency: Examples from the Food Processing Industry

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Abstract

For over 25 years, the U.S. DOE's Industrial Technologies Program (ITP) has championed the application of emerging technologies in industrial plants and monitored these technologies' impacts on industrial energy consumption. The cumulative energy savings of more than 160 completed and tracked projects is estimated at approximately 3.99 quadrillion Btu (quad), representing a production cost savings of $20.4 billion. Properly documenting the impacts of such technologies is essential for assessing their effectiveness and for delivering insights about the optimal direction of future technology research.

This paper analyzes the impacts that several emerging technologies have had in the food processing industry. The analysis documents energy savings, carbon emissions reductions and production improvements and assesses the market penetration and sector-wide savings potential. Case study data is presented demonstrating the successful implementation of these technologies. The paper's conclusion discusses the effects of these technologies and offers some projections of sector-wide impacts.

Introduction

In the United States, the industrial sector accounts for 33% of total energy consumption (42). Emerging technologies have the potential to significantly reduce industrial energy consumption and improve productivity by increasing the energy efficiency of industrial processes and systems. Therefore, the adoption of such technologies is important because they enable manufacturing plants to become both more competitive and productive. However, because firms have limited financial resources to invest in new capital stock, emerging technologies compete for funding with longstanding or mature technologies. By analyzing the impact of some promising emerging technologies on energy consumption in the U.S. food processing industry, we show that the adoption of emerging technologies is highly compelling for U.S. industry.

In this study, we analyze four emerging and recently commercialized technologies have had in the U.S. food processing industry. We find that these technologies have significant potential for improving process energy efficiency. In addition, these technologies have yielded important productivity and other benefits. Based on these results, we assess the potential magnitude of energy savings and other benefits for the industry. We estimate that on an sector-wide level, the systematic implementation of these four emerging technologies could reduce annual energy consumption by up to 2.22 TBtu and 186 million kWh depending on the industry's adoption rate. We also show that the food industry's productivity could be enhanced, which could result in higher output and better profitability, and that carbon emissions could be significantly reduced.

For the purposes of this paper emerging technologies are defined as technologies that embody the latest in efficiency and productivity design that have most recently been commercialized. Such technologies have been tested for performance and reliability under laboratory conditions and field demonstrations. These technologies cease to be considered emerging after having been successfully commercialized for ten years. They are typically installed first in new or recently upgraded plants.

We begin with a discussion of the DOE's support of emerging technologies and how it assists in commercializing promising, energy efficient technologies. Next, we review the U.S. food processing industry and the manner in which this industry adopts energy efficiency equipment and methodologies. Then, we discuss several newly commercialized and emerging technologies that have begun to generate energy savings in productivity improvements within the U.S. food processing industry. We present some case study data and analyze the market penetration potential, paybacks and sector-wide savings from these technologies. We conclude with an assessment of the U.S. food industry's future energy savings potential and the role that emerging technologies could have in achieving such savings.

The U.S. Department of Energy's Industrial Technologies Program

The U.S. Department of Energy's (DOE) Industrial Technologies Program (ITP), part of the Office of Energy Efficiency and Renewable Energy (EERE), began to champion the implementation of new and emerging technologies in 1979. EERE was attracted to the potential of such technologies for reducing industrial energy consumption and improving industrial productivity, thereby stimulating economic growth. ITP invests in experimental technologies holding the promise of yielding important energy savings and additional benefits. The investments are targeted towards energy saving technologies and practices that are beset with market barriers, which prevent adequate private sector investment for them to be rapidly and fully commercialized.

ITP applies a six-step strategy in its advocacy of emerging technologies. The first step is to concentrate on the most energy intensive industries. This led to the creation of ITP's Industries of the Future (IOF) category that helped channel efforts to create opportunities to improve energy efficiency in the most energy-intensive industries. ITP also fosters public-private partnerships to plan and fund joint research, focus on specific problems, and shepherd the commercialization of the most promising projects. The third step involves identifying and analyzing the barriers that inhibit industrial energy efficiency to come up with ways to overcome them. The next part of its strategy is to apply equal weight to research and development (R&D), validation of the R&D results, and distribution of the technologies to the industries that possess the greatest need to improve energy efficiency. The fifth step is to identify and support process-specific and crosscutting R&D in technologies that benefit the public, but are not necessarily attractive to industry. Lastly, ITP assists with technology delivery activities to ensure the technologies developed yield improvements in industrial energy efficiency. ITP does this by sponsoring plant assessments, funding technical assistance and arranging for showcase demonstrations at industrial facilities to expose the effectiveness of emerging technologies.

ITP also uses a rigorous internally based monitoring system to gauge the effectiveness of the technologies it supports. Before emerging technologies are commercialized, their energy savings potential is estimated by Pacific Northwest National Laboratory (PNNL). When a technology's full-scale commercial unit is operational in a commercial setting, that technology is then considered commercially successful and is actively monitored. When a commercially successful technology unit has been in operation for about ten years, it is then considered a mature technology and is typically no longer actively tracked.

Since it started championing emerging technologies, ITP has supported more than 600 separate research, development, and demonstration (RD&D) projects producing over 160 new, energy efficient technologies (42). Many of these technologies have been commercialized in various industrial settings and ITP has monitored their implementation and assessed their energy savings. Examples of these technologies include an aluminum scrap decoater, an evaporator fan controller for refrigeration, and a variable frequency microwave furnace (42). The aggregate energy savings resulting from more than 160 completed and tracked projects and other ITP programs is approximately 3.99 quadrillion Btu (quad), representing a cost savings of $20.4 billion (42). In addition to these energy and energy cost savings, these projects have yielded non-energy benefits such as productivity gains, reduced maintenance costs, better product quality, lower resource consumption and decreased emissions.

The U.S. Food Processing Industry

The U.S. food processing industry is one of the largest industrial sectors in the U.S. In 2004, annual production from food processing (NAICS code 311 and 312) was worth about $559 billion (37), which represented approximately 13% of the total value of shipments from all U.S. manufacturing sectors. The industry includes over 35,000 food-processing facilities employing about 1.5 million people (9). In 2003, the typical U.S. household devoted 13.2 percent of after-tax income to the purchase of food and beverage products (45). In addition, the food industry is one of the few in which trade surpluses are typically recorded (1). Therefore, the U.S. food processing industry is vital to the U.S. economy and in foreign trade due to its large size, stability, growth, diverse products, and competitive nature.

The food processing industry performs a broad range of industrial processes falling into two broad categories: preservation and non-preservation. Preservation processes prepare food for end-use consumption. They are designed to ensure freshness, quality, safety and cleanliness. These processes involve the introduction of heat, cold temperatures or chemicals to inactivate microorganisms, alter the texture, flavor, or otherwise preserve food. They include cooking, boiling, baking, drying, refrigerating/freezing, dehydration, pasteurizing, fermentation, and irradiation. Different types of cooking processes increase the storage stability of foods, while refrigeration or freezing can preserve food for months.

Non-preservation processes are designed to achieve various effects. Some of these processes extract nutrients, while others alter the texture of food or convert it to another state for easier preservation, storage or transportation. Many of these processes prepare foods for preservation or finish them after preservation. They include peeling, chopping, cutting, assembly, packaging, separation (condensing/evaporating), and waste management.

The U.S. food processing industry uses energy for many preservation and non-preservation processes, particularly safe packaging and storage. Approximately half of all energy end-use consumption is used in processes changing raw materials into products (1). These processes include process heating and cooling, refrigeration, machine drive (mechanical energy), and electro-chemical processes. Of these, process heating uses approximately 29% of total energy in the food industry, while process cooling and refrigeration demands about 16% of total energy inputs (1). Thermal processing and dehydration are the most commonly used techniques for food preservation, and require significant amounts of energy. Boiler fuel, particularly natural gas, represents nearly one-third of end-use consumption and is mainly used to produce steam. Processing uses 78% of electricity, with 48% used for machine drive and 25% for process cooling and refrigeration. Non-process uses account for 16% of electricity use (1). This is shown in Table 1. In 2002, the food industry accounted for 5.4% of the total purchased energy by the manufacturing sector – 9% of the electricity and 9.7% of natural gas are used in the U.S. food sector (9). This is shown in Table 2.

End-Use Consumption	**Percent of Total Energy Inputs Used**
Process Heating	29%
Process Cooling & Refrigeration	16%
Steam Production	33%
End-Use Consumption	**Percent of Electricity Used**
Processing	78%
Processing by Machine-driven equipment	48%
Process Cooling & Refrigeration	25%
Non-Process	16%

Table 1: Energy Used in the Food Processing Industry

	Total (trillion btu)	Net Electricity (million kWh)	Natural Gas (billion cu ft)	Coal (million short tons)
NAICS code 311 & 312	1,228	75,160	612	9
Total U.S. Manufacturing	22,666	832,061	6,298	84
Percentage of U.S. Total	5.4%	9.0%	9.7%	10.7%

Source: MECS 2002

Table 2: U.S. Food Industry Energy Use 2002

The U.S. food processing industry has historically been slow to adopt new technologies. The first reason for this is industry conservatism (9). Because the food processing industry is closely monitored by federal and state governments to ensure compliance with safety and sanitation standards, any new methodologies or technologies must be thoroughly tested and be able to pass these requirements. As a result, food processing companies have been reluctant to innovate without knowing whether a new process or technology will meet safety and sanitation standards and have tended to rely on established technologies or expertise in marketing and distribution to maintain or gain market share. This has also caused food-processing firms to depend on technological innovations in the chemical and biotechnology sectors. Processes such as separation, condensation, oil seed extraction and wet corn milling were originally perfected in the chemical industry and later adopted by food processors once such processes were deemed appropriate.

The second principal reason for historically slow adoption of emerging technology is the cost of the R&D. R&D can be expensive, and due to the industry's low profit margins, many food processing firms cannot undertake a lot of in-house research. Also, the cost of R&D leads to high capital costs, which are hard to accept given the industry's profit margins. Another factor limiting early adoption of emerging technologies in the food processing industry is the industry's competitiveness. Because the industry is highly competitive, firms are reluctant to collaborate and are secretive about new processes and technologies. Additional reasons include technology awareness and situations in which the benefits of a specific technology are not always understood until the technology is mature.

Four Emerging Technologies that have Impacted the Food Processing Industry

This section presents the results of four assessments that were recently conducted on promising emerging energy-efficient technologies in the U.S. food processing industry. An outline of the assessment method is provided in Figure 1. First, a literature review was performed to select several promising emerging technologies in the food processing industry for further consideration. Particular emphasis was placed on technologies identified through the U.S. DOE ITP emerging technologies program. Based on the literature review, four emerging technologies were chosen for detailed assessment: energy-efficient blanching, pulsed electric field (PEF) pasteurization, radio frequency (RF) drying, and evaporator fan controllers for refrigerated cold storage. Descriptions of these technologies are provided in the case study results that follow. These particular technologies were chosen due to their promise for reducing industrial energy consumption and/or improving productivity and because adequate case study and performance data for these technologies were available in the public domain.

For each technology, a representative target sector in the U.S. food processing industry was then selected for detailed assessment. A target sector was defined as a single industrial sector for which a given emerging technology was deemed to have the greatest potential for future market penetration. The assessment for each technology was limited to a single target sector to ensure that results were based on the most realistic application scenarios for each technology and for ease of data collection. However, the four emerging technologies are also likely to find application in additional food industry sectors not considered here.

Within each target sector, the existing technologies ("base technologies") that the emerging technology was expected to either augment (via retrofit) or replace were identified. Representative specific energy consumption values (i.e., Btu/lb. of product processed) were then compiled for base technologies from publicly available data sources;

where possible, typical ranges of specific energy consumption were identified.

Next, the total energy use of base technologies in each target sector was projected from 2005-2020. A 15-year analysis period was chosen to acknowledge that emerging technologies are typically adopted slowly; as a result, it often takes years before an emerging technology achieves significant market penetration (21). It was therefore assumed that by 2020, the selected emerging technologies would have sufficient time for market penetration at realistic annual penetration rates. The total energy use of base technologies in 2020 was calculated by first estimating current (2005) energy use, and then projecting energy use to 2020 based on the historical annual growth rate of the applicable target sector. These projections provided a baseline from which the energy savings potential of each emerging technology in 2020 could be calculated.

Next, the available market portion within each target sector for emerging technology adoption was estimated. The available market portion was defined as the percentage of base technology installations that could realistically be augmented or replaced by the emerging technology over the 15-year analysis period. Replacement refers to when the emerging technology replaces the base technology in its entirety. For emerging technologies that would replace base technologies, the available market portion was estimated by dividing the typical useful life of the base technologies by the analysis period (15 years) (21). This calculation provided a rough estimate of the market portion available through demand for new equipment. For emerging technologies that are retrofit applications, the available market portion was assumed to be 100%. Retrofit applications are those emerging technologies that are added-on to existing equipment.

Finally, an available market portion penetration rate of 10% per year was assumed for each emerging technology. This assumption was based on previous work by Martin et al. (21), which estimated a 10% per year market penetration rate for emerging technologies that have minimal market barriers. While the market barriers associated with the four emerging technologies considered in this assessment may or may not be "minimal" (market

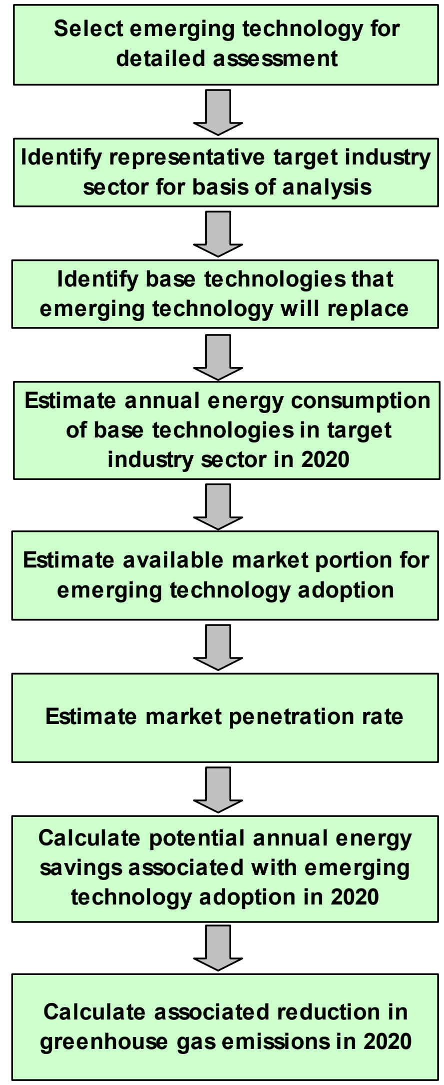

Figure 1. Emerging technology assessment methodology.

barriers are discussed the case studies below), the most optimistic market penetration rate was chosen to provide an upper bound on the technical potential for energy savings associated with each emerging technology.

Based on the assessment steps above, the technical potential for energy savings attributable to each emerging technology in its target industry sector in 2020 was calculated. Projected savings were calculated in terms of both delivered energy (i.e., natural gas and electricity consumed at the plant) and primary energy (i.e., the fossil fuels consumed in electricity generation). Electricity savings were converted to primary energy using regional weighted average fossil fuel intensity values (Btu/kWh). These regional weighted averages were derived from state-specific fuel mixes for electricity generation (39) based on the share of production (value added basis) of each U.S. state within a target industry sector (31).

In addition to energy savings, the technical potential for reductions in carbon dioxide (CO_2) emissions was also calculated for each emerging technology. Savings in natural gas were converted to avoided CO_2 emissions using a conversion factor of 5.3e-05 kg CO_2 per Btu of natural gas (46). Savings in electricity were converted to avoided CO_2 emissions using regional weighted average CO_2 emission intensity values (kg CO_2/kWh), which were calculated using state-specific electricity generation CO_2 emissions data (40) based on the share of production of each U.S. state. To put the potential CO_2 savings into perspective, avoided CO_2 emissions are equated to equivalent CO_2 emissions from U.S. automobiles, using a conversion factor of 4,600 kg of CO_2 per automobile per year (32).

The results of the emerging technology assessments are provided below. For each emerging technology, a brief discussion of non-energy benefits and potential market barriers is offered. Where possible, case study data are also presented as an example of savings achieved in industrial applications to date.

Energy-Efficient Blanching

Blanching is an important unit process in fruit and vegetable processing, in which raw materials are subjected to elevated temperatures for a few minutes to inactivate enzymes prior to further processing (e.g., canning or freezing). The most common methods of blanching involve passing raw materials through an atmosphere of saturated steam or a hot water bath (14). Common types of blanchers include belt tunnels (steam), rotary (steam), hydrostatic (steam), reel (hot water), and tubular (hot water) (26; 14). Energy-efficient blanchers employ fully insulated cabinets, utilize hydrostatic seals or water curtains to reduce evaporation, and recirculate the energy medium to the greatest extent possible in order to minimize process energy use. At least one energy efficient blancher, the Turbo-Flo Blancher/Cooker, has demonstrated energy savings of between 30% and 70% compared to traditional blanchers under laboratory conditions (48).

The assessment results for energy-efficient blanching are summarized in Table 1. Vegetable canning was chosen as the target industry sector – specifically, the canning of asparagus, lima beans, snap beans, carrots, corn, peas, and spinach – given its high production volumes and widespread use of blanching. Over 5 billion pounds per year of the above vegetables are processed for canning (39); this amount was projected to grow by 0.1% per year through 2020 based on historical data from the United States Department of Agriculture (33). All major types of steam and water blanchers were considered as base technologies. Published estimates of the specific energy consumption of the base technologies ranged from 375-800 Btu/lb. (natural gas) (27; 6; 15). The available market portion was estimated to be 60%, based on an estimated average blancher life of 25 years. Using available data (48) and software tools the natural gas savings potential of the energy-efficient blancher was estimated at from 30% and up to 70% when productivity improvements were factored in.

The results in Table 3 suggest that the technical potential for energy savings ranges from roughly 0.7 TBtu to 1.5 TBtu of natural gas per year. When avoided CO_2 emissions are considered, the projected energy savings would be equivalent to taking 7,700 to 16,600 average automobiles off U.S. roads each year.

The non-energy benefits of energy-efficient blanchers include reduced wastewater generation, increased product throughput due to shorter blanching times, more consistent product quality due to more even and thorough product heating, and reduced floor space utilization. One case study example is Hanover Foods in Hanover, Pennsylvania, which installed an energy efficient blanching system in 2005. They have used it to blanch green beans, carrots, celery, potatoes and sweet potatoes. Water use was reduced by 10%. Energy costs and energy consumption related to blanching decreased by 4% and 10% respectively. The energy cost reduction would have been higher, but for significantly higher energy costs over the previous year. Finished product quality also improved over water blanching. Unterseher (48) provides case study data for two additional industrial applications. Reser's Fine Foods, a manufacturer of fresh salads and refrigerated potato products based in Beaverton, Oregon, installed four energy-efficient blanchers and realized a 300% increase in production throughput and at the same time reduced the necessary floor space for blanching dramatically. The California Prune Packing Company, in Live Oak, California, cited increased product quality and energy savings by retrofitting an energy efficient blancher, which led to a simple payback period of less than two years.

Assessment Parameter	Value
Target industry sector	Vegetable canning
Current annual production	5,350,000,000 lb./year
Base technologies	Standard steam and hot water blanchers
Production growth through 2020	0.1%/year
Specific energy consumption of base technologies	375-800 Btu/lb. (natural gas)
Projected annual energy consumption of base technologies in 2020 (primary)	2.04-4.41 TBtu/year (natural gas)
Projected annual CO_2 emissions of base technologies in 2020	106-230 kt CO_2/year
Replacement or retrofit technology?	Replacement
Base equipment useful life	30 years
Available market portion	60%
Energy savings of emerging technology	30% - 70%
Results	**Value (Technical Potential)**
Energy savings potential in 2020 (primary)	0.24 to 0.52 and 0.56-1.22 TBtu/year (natural gas)
CO_2 emissions reduction potential in 2020	29-64 kt CO_2/year
Equivalent automobiles	6,400-13,870 automobiles/year

Table 3. Assessment assumptions and results for energy-efficient blanching.

No significant market barriers were identified. However, because it has a higher cost than traditional blanchers and the fact that blanchers are fairly simple and last a long time, firms might have greater incentive to fix existing blanchers instead of buying new equipment.

Pulsed Electric Field Pasteurization

Pasteurization is a mild form of heat treatment, whose purpose is to minimize health hazards from harmful micro-organisms (bacteria, viruses, etc.) in food products and to extend product shelf life. Typical pasteurization temperatures are less than 100 degrees C (14). Pasteurization is used extensively for beverage manufacturing in the dairy, brewery, and fruit juice industries. A common approach to pasteurization in beverage manufacturing is to circulate fluids through continuous flow (plate or shell-in-tube) heat exchangers, which use steam or hot water as the energy medium and retain fluids for a predetermined residence time necessary to ensure micro-organism inactivation. Some products are also subjected to cooling immediately after pasteurization to minimize the effects of heat on product taste, color, and quality. Pulsed electric field pasteurization is an emerging non-thermal method of pasteurization, in which food products are exposed to external, high voltage pulses of electricity that break down biological cells and inactivate micro-organisms. The advantages of PEF pasteurization include lower processing temperatures, shorter product residence time, and minimal deterioration of food quality (30).

The assessment results for PEF pasteurization are summarized in Table 3. Not-from-concentrate (NFC) orange juice manufacturing was chosen as the target industry sector, because the rising popularity of NFC orange juice in world markets has resulted in high annual production volumes and significant growth potential. Additionally, recent tests of PEF pasteurization methods on orange juice have shown that PEF processing leads to similar micro-organism inactivation as traditional pasteurization methods but with improved color and flavor retention (5). Current annual production of NFC orange juice is estimated at over 5.2 billion pounds per year (28; 33), with annual production growth potential of nearly 5% through 2020 based on historical data (28; 16: 6). Conventional continuous flow heat exchangers (plate and shell-in-tube) were selected as the most representative base technologies. The specific energy consumption of the base technologies was estimated at 166 Btu/lb. natural gas (for heating) (6) and 0.03-0.04 kWh/lb. electricity (for cooling) (3). The average lifespan of the base technologies was estimated at 25 years, leading to a predicted available market portion of 60%.

Assessment Parameter	Value
Target industry sector	NFC orange juice manufacturing
Current annual production	5,250,000,000 lb./year
Base technologies	Continuous heat exchangers (plate or shell in tube)
Production growth through 2020	5%/year
Specific energy consumption of base technologies (delivered)	0.03-0.04 kWh/lb. (electricity)
	166 Btu/lb. (natural gas)
Regional weighted average fossil fuel intensity of electricity generation	7,380 Btu/kWh
Regional weighted average CO_2 emissions from electricity generation	0.6 kg CO_2/kWh
Projected annual energy consumption of base technologies in 2020 (delivered)	327-436 GWh/year (electricity)
	1.8 TBtu/year (natural gas)
Projected annual energy consumption of base technologies in 2020 (primary)	4.2-5.0 TBtu/year (fossil fuel equivalents)
Projected annual CO_2 emissions of base technologies in 2020	290-355 kt CO_2/year
Replacement or retrofit technology?	Replacement
Base equipment useful life	25 years
Available market portion	60%
Energy savings of emerging technology (natural gas)	100%
Energy savings of emerging technology (electricity)	-10% to 18%
Technical Potential Results	**Value**
Energy savings potential in 2020 (delivered)	0.86 TBtu/year (natural gas)
	-15-36 GWh/year (electricity)
Energy savings potential in 2020 (primary)	0.75-1.04 TBtu/year (fossil fuel equivalents)
CO_2 emissions reduction potential in 2020	35-66 kt CO_2/year
Equivalent automobiles	7,800-14,500 automobiles/year

Table 4. Assessment assumptions and results for PEF pasteurization.

The specific energy consumption of PEF pasteurization was estimated at 0.033 kWh per pound of processed fluid (8). Because the vast majority of U.S. orange juice production occurs in Florida (24), the fossil fuel intensity (7,380 Btu/kWh) (33) and CO_2 intensity (0.6 kg CO_2/kWh) (35) of electricity generation in Florida were employed. The natural gas savings of PEF pasteurization were estimated at 100%, since thermal processing is eliminated. The electricity savings of PEF pasteurization ranged from -10% (i.e., a net gain in electricity consumption) to 18% based on the assumed electricity consumption range of the base technologies.

The results in Table 4 suggest that the technical potential for natural gas savings amounts to roughly 0.9 TBtu per year; however, electricity savings are less certain as the switch to PEF pasteurization may increase the consumption of delivered electricity. Whether a net decrease or increase in electricity consumption is realized depends on the electricity that is saved by avoiding post-pasteurization cooling, which will vary from plant to plant. However, when total primary energy is considered, it can be seen that PEF pasteurization is still less energy intensive than traditional pasteurization methods, leading to annual savings of 0.75-1 TBtu per year of fossil fuel equivalents. Significant savings in CO_2 emissions (up to 66 kt CO_2/year) are also realized.

In addition to energy savings, PEF pasteurization can lead to productivity increases through reduced residence times and product quality improvements through better color and flavor retention that makes PEF processed juices more “fresh like” (30). The Genesis Juice Corporation, a maker of premium refrigerated natural fruit juice products, has installed a 200-liter per hour PEF pasteurizer in its Eugene, Oregon plant (7). Genesis cites the main motivation for PEF processing as the avoidance of loss of flavor from normal thermal pasteurization methods. The shelf life of Genesis juices processed via PEF is four weeks.

The primary market barrier to PEF pasteurization is high capital costs compared to traditional pasteurization methods, partly due to the relatively small market for electrical pasteurization equipment (7). Reliability can also be an issue, with electrodes needing replacement about every 100 hours of operation. Research is underway to improve electrode reliability. Lastly, PEF pasteurization methods are not well suited for certain vegetable juices, such as carrot juice, which need to be acidified to achieve proper micro-organism inactivation (7).

Radio Frequency Drying

Radio frequency heating methods have been under investigation for decades, and have recently found use in the food processing industry for product cooking, baking, and drying applications. Radio frequency heating works by bombarding food products with electromagnetic waves in the 30-300 MHz spectrum, which causes water molecules in food products to rapidly vibrate and generate heat uniformly throughout the product via friction (49). Rapid heating is the primary advantage of RF heating, allowing for faster line speeds and shorter line lengths. RF heating selectively heats only the product and not the air or equipment surrounding it, and products are heated evenly and uniformly (50).

In the food industry, the primary application of RF heating to date has been in post-bake drying applications for cookies, crackers, and pasta (23). In the conventional baking process, an oven is divided into three stages: (a) product loft development, (b) product baking, and (c) product drying, where the final product dryness is achieved (7). By adding an RF drying unit to the end of the oven line, the drying burden on the third stage of the oven is eliminated, allowing the belt speed of the oven to be increased by 30-60% (7; 19; 22; 29). The increased productivity can lead to a reduction in the specific energy consumption of the oven (Btu/lb.), since more product is being processed using the same amount of oven energy. However, additional energy is consumed by the RF dryer (in the form of electricity), which suggests that RF drying may be more appropriately classified as a fuel switching technology than a true energy saving one. The specific energy consumption of RF drying has been estimated at roughly 1 kWh per kg of water in the product (17; 15).

Using the original data (assumed value of 1 kWh per kg of water), the analysis showed that RF drying led to increases in net energy consumption. Publicly-available estimates of the specific energy consumption of tunnel ovens were found to vary widely; typical values in the literature ranged from 250 Btu/lb. (natural gas) to 1750 Btu/lb. (natural gas) (27; 6; 15; 13). For ovens in which the specific energy consumption was on the lower end of the range, the analysis showed that RF drying is not expected to yield net energy savings, though it is expected to yield productivity gains. Therefore, we present the analysis for a range of energy consumption that will yield net energy savings. Mathematically, the minimum oven specific energy consumption for which RF drying will lead to net energy savings can be expressed by:

$$x_{min} = z(1+y)/y \qquad \text{(i)}$$

Where: x_{min} = minimum specific energy consumption of oven (Btu/lb.)
y = productivity increase realized by addition of RF dryer (%)
z = specific primary energy consumption of RF dryer (Btu/lb.)

The assessment results for RF drying are summarized in Table 5. The cookies and crackers manufacturing industry was chosen as the target industry sector, based on the installed applications of RF drying technology to date. The current production output of this sector was estimated at over 5.4 billion pounds of product per year (15). Based on historical production data obtained from the U.S. Census Annual Survey of Manufacturers, it was estimated that the annual growth rate of the target industry sector through 2020 would be 0.1%. Direct-fired tunnel ovens were chosen as the base technology, as this oven type is commonly used in large-scale snack food manufacturing operations (14).

Based on equation (i), however, it was determined that RF drying would only lead to energy savings for tunnel ovens with specific energy consumption greater than 850 Btu/lb. This estimate was based on assumed values for the average productivity increase (40%) and specific primary energy consumption (240 Btu/lb.) of RF drying units; the latter value was calculated based on published values of RF dryer energy consumption (17; 15), an assumed average product moisture content of 7.5% (25), and the estimated regional weighted average fossil fuel intensity for electricity generation (7,290 Btu/kWh) (33). The top producing U.S. states (on a value-added basis) were found to be Illinois, Pennsylvania, Georgia, and Ohio (31).

Although RF drying is a retrofit application, the available market portion for this emerging technology was estimated at only 25%. This estimate was based on the assumption that only 25% of tunnel ovens would have specific energy consumption of 850 Btu/lb. or greater, the minimum value necessary for energy savings based on typical productivity increases. The assumption of 25% was based on oven performance survey data that have been published for European bakeries (4).

The estimated natural gas savings in 2020 ranged from 0.07 TBtu to 0.14 TBtu per year, which are savings realized at the plant level. However, energy savings from natural gas are offset by the increase in electricity necessary to power the RF drying unit. It was estimated that roughly 8 GWh per year would be consumed by RF drying units in 2020. Depending on the natural gas consumption of the base tunnel oven, the primary energy savings range from zero to 0.07 TBtu per year. Thus, it is clear that RF drying makes the most sense from a primary energy perspective when augmenting fairly energy-intensive tunnel ovens. From a CO_2 emissions perspective, however, the environmental benefits of RF drying are less certain. The results in Table 4 suggest that CO_2 reductions are only realized for the most energy-intensive ovens considered in the assessment.

Assessment Parameter	**Value**
Target industry sector	Cookies and crackers manufacturing
Current annual production	5,420,000,000 lb./year
Base technologies	Direct fired tunnel ovens
Production growth through 2020	0.1%/year
Specific energy consumption of base technologies (delivered)	0.004 kWh/lb. (electricity)
	850-1750 Btu/lb. (natural gas)
Regional weighted average fossil fuel intensity of electricity generation	7,290 Btu/kWh
Regional weighted average CO_2 emissions from electricity generation	0.57 kg CO_2/kWh
Projected annual energy consumption of base technologies in 2020 (delivered)	5 GWh/year (electricity)
	1.2-2.4 TBtu/year (natural gas)
Projected annual energy consumption of base technologies in 2020 (primary)	1.2-2.4 TBtu/year (fossil fuel equivalents)
Projected annual CO_2 emissions of base technologies in 2020	64-128 kt CO_2/year
Replacement or retrofit technology?	Retrofit
Available market portion	25%
Energy savings of emerging technology (natural gas)	29%
Energy savings of emerging technology (electricity)	-840%
Technical Potential Results	**Value**
Energy savings potential in 2020 (delivered)	0.07-0.14 TBtu/year (natural gas)
	-8 GWh/year (electricity)
Energy savings potential in 2020 (primary)	0-0.07 Btu/year (fossil fuel equivalents)
CO_2 emissions reduction potential in 2020	-1.5-2.1 kt CO_2/year
Equivalent automobiles	-330-470 automobiles/year

Table 5. Assessment assumptions and results for RF drying

Radio frequency dryers have been installed successfully in post-baking applications at numerous companies, leading primarily to productivity increases. (7; 29; 2). At the Sunshine Biscuit Company in the Los Angeles area, the addition of a post-bake RF drying unit led to a 30% increase in production, a reduction in annual purchased energy equivalent to 600 barrels of oil, and a $715,000 reduction in operating and maintenance costs (29). In addition to energy efficiency (for ovens where the addition of RF drying leads to energy savings), cited benefits include increased product throughput, reduced floor space requirements, increased product quality via reduced "checking" (when the surfaces of baked goods crack after drying), and low maintenance costs (19; 23; 29; 10).

The current market barriers to RF drying technology include high initial capital costs of the equipment due to immature market demand, the need for skilled labor required for equipment tuning, and the vulnerability of RF drying to fluctuations in electricity prices (23; 10).

Evaporator Fan Controls for Refrigerated Storage

Refrigeration is an important and nearly ubiquitous unit process in the U.S. food processing industry. Refrigeration can be used for preserving raw materials prior to processing (e.g., cold storage of harvested vegetables), for chilling products between process steps (e.g., buffer storage in meat packing), and for storing finished products before they are shipped to the marketplace (e.g., cold storage of bottled milk). The use of advanced evaporator fan controllers can reduce the energy consumption of refrigeration significantly, by regulating the speed of fan motors to better match the needs of the refrigeration cycle. According to the DOE, such controllers can reduce a refrigeration system's evaporator and compressor energy use by up to 50% and, as of 2000, have led to cumulative energy savings of over 6 billion Btu in the United States (43; 44). One large cold storage company, Henningsen Cold Storage, has installed this technology in at least four facilities that have resulted in annual energy savings of 20%.

The assessment results for evaporator fan controllers are summarized in Table 6. Fluid milk manufacturing is one of the key users of refrigeration systems in the U.S. food processing industry, and was therefore chosen as the target industry sector. An estimated 56 billion pounds of fluid milk and cream products are produced in the United States each year (33; 35). The annual growth rate through 2020 was estimated at 1% based on historical fluid milk production data (36). Conventional ammonia-based refrigeration systems were identified as the most representative base technologies in the target industry sector. The specific energy consumption of the base technologies was estimated at 0.008 kWh per pound of stored milk, based on an average value obtained from 17 Canadian dairy plants (12). Since evaporator fan controllers are a retrofit technology that is suitable for most refrigeration systems, the available market portion was estimated at 100%. The savings in electricity achievable via installation of evaporator fan controllers was estimated at 50% (43; 44).

Fluid milk manufacturing occurs throughout the United States; however, on a value added basis the top producing states (in descending order) are California, Texas, Ohio, New York, Michigan, and Pennsylvania (31). The regional weighted average fossil fuel intensity of electricity generation for fluid milk manufacturing was estimated at 8,000 Btu/kWh (39). The regional weighted average CO_2 intensity of electricity generation was estimated at 0.6 kg CO_2/kWh (40).

The results in Table 6 suggest that the technical potential for energy savings amounts to roughly 197 GWh of electricity per year, or 1.6 TBtu of fossil fuel equivalents. Avoided CO_2 emissions total 115 kt of CO_2 per year, which is equivalent to taking over 25,000 average automobiles off U.S. roads each year. According to the U.S. DOE's ITP (43), this technology has

- saved over 6 billion Btu cumulatively through 2000
- reduced evaporator and compressor energy consumption by 40% to 50%
- saved $80,000 in energy purchases through 2000
- avoided 425 tons of CO_2 emissions through 2000
- been installed on over 1400 refrigeration applications since 1997.

Assessment Parameter	Value
Target industry sector	Fluid milk manufacturing
Current annual production	56,100,000,000 lb./year
Base technologies	Conventional ammonia-based refrigeration systems
Production growth through 2020	1%/year
Specific energy consumption of base technologies (delivered)	0.008 kWh/lb. (electricity)
Regional weighted average fossil fuel intensity of electricity generation	8,010 Btu/kWh
Regional weighted average CO_2 emissions from electricity generation	0.6 kg CO_2/kWh
Projected annual energy consumption of base technologies in 2020 (delivered)	501 GWh/year (electricity)
Projected annual energy consumption of base technologies in 2020 (primary)	4 TBtu/year (fossil fuel equivalents)
Projected annual CO_2 emissions of base technologies in 2020	293 kt CO_2/year
Replacement or retrofit technology?	Retrofit
Available market portion	100%
Energy savings of emerging technology	40-50%
Technical Potential Results	**Value**
Energy savings potential in 2020 (delivered)	158 to 197 GWh/year (electricity)
Energy savings potential in 2020 (primary)	1.27 TBtu/year (fossil fuel equivalents)
CO_2 emissions reduction potential in 2020	93 kt CO_2/year
Equivalent automobiles	20,200 automobiles/year

Table 6. Assessment assumptions and results for evaporator fan controllers.

Conclusion

Many emerging technologies can show promise for industrial energy efficiency on a laboratory or pilot application scale. The U.S. DOE's ITP has championed the implementation of such technologies in U.S. industrial facilities for over 25 years. This paper assessed the energy efficiency potential for four of these technologies in the U.S. food processing industry. Based on the assessments of these four emerging and newly commercialized technologies, the potential for energy savings in the U.S. food industry is quite strong. In addition, these technologies have yielded important productivity and other benefits. Depending on the available market portions in which these technologies can be implemented, sector-wide energy savings could range from 1.49 TBtu and 134 million kWh to 2.22 TBtu and 186 million kWh. In addition, non-energy benefits such as improved product quality, better production and reduced greenhouse gas emissions are likely. In the case of RF drying, the average productivity increase has been demonstrated at 40%. As another example, the average product-to-steam ratio for a energy efficient blancher processing cauliflower was 42% higher than that of a conventional blancher. We estimate that CO_2 emissions reductions could range from 123 million kg to 249 million kg. These results suggest that the adoption of such technologies is compelling for the U.S. food processing industry.

References

1) American Council for an Energy Efficient Economy “A Review of Energy Use in the Food Industry”, Washington, D.C., http://www.aceee.org/pubs/ie981.htm

2) Anonymous, 2004, "Pepperidge Farm & the Quest for What's Next," Snack Food & Wholesale Bakery Magazine, Deerfield, Illinois, February.

3) Australian Department of Industry, Tourism, and Resources (DITR), 2002, Pasteurisation Options for Breweries, Canberra, Australia. http://www.industry.gov.au/assets/documents/itrinternet/Pasteurisationoptionsforbreweries20040212081239.pdf

4) Austrian Energy Agency, 2001, Energy Benchmarking at the Company Level: Company Report Bakery, Vienna, Austria. http://www.eva.ac.at/(en)/projekte/ideen2.htm

5) Ayhan, Z., Q.H. Zhang, and D.B. Min, 2002, "Effects of Pulsed Electric Field Processing and Storage on the Quality and Stability of Single-Strength Orange Juice," Journal of Food Protection, 65(10), pp. 1623-1627.

6) Brown, H., B.B. Hamel, and B.A. Hedman, 1996, Energy Analysis of 108 Industrial Processes, Fairmont Press, Lilburn, Georgia.

7) Clark, Peter. “Pulsed Electric Field Processing”, Food Technology, January 2006, Pg. 66-67

8) Clark, T.D., 1997, "The Current Status of Radio Frequency Post-Baking Drying Technology," Proceedings of the 72nd Annual Technical Conference of the Biscuit and Cracker Manufacturer's Association, Fort Worth, Texas, October 21. http://www.radiofrequency.com/products/current.html

9) Electric Power Research Institute “Food Industry Scoping Study”, Palo Alto, California (1990).

10) Energy Center of Wisconsin, 2000, "Radio Frequency Drying Fact Sheet," Madison, Wisconsin.

11) Energy Information Administration “2002 Manufacturing Energy Consumption Survey”, Washington, D.C., http://www.eia.doe.gov/emeu/mecs/contents.html

12) Environment Canada, 2001, Energy Performance Indicator Report: Fluid Milk Plants, Ottawa, Ontario. http://oee.nrcan.gc.ca/Publications/industrial/fluid-milk-plants/BenchmDairy_e.pdf

13) European Commission, 2006, Integrated Pollution Prevention and Control Reference Document on the Best Available Techniques in the Food, Drink, and Milk Industries, Brussels, Belgium. http://eippcb.jrc.es/cgi-bin/locatemr?fdm_final_0106.pdf

14) Fellows, P.J., 2000, Food Processing Technology: Principles and Practice, CRC Press, Boca Raton, Florida.

15) Gas Technology Institute, 2003, Research Collaboration Program Food Processing Technology Project Phase 1, Des Plaines, Illinois. Report # GRI-03/0075.

16) Goodrich R. M. and Brown, M. G. “European Markets for NFC: Supply and Demand Issues” Florida Department of Citrus, Gainesville, Florida 2001 http://www.floridajuice.com/gr_market_list_misc.php

17) James, T.W., 1996, "RF Drying Provides Process Savings," Ceramic Industry Magazine, April.

18) James, T.W, 2006, Personal communication with T.W. James of Radio Frequency Company Inc., February 28, 2006.

19) Koral, T., 2004, "Radio Frequency Heating and Post-Baking," Strayfield Frastran, Berkshire, England, UK. http://www.strayfieldfastran.co.uk/images/Radio%20Frequency%20Heating%20and%20Post%20Baking.pdf

20) Kranjcevic, E., 2004, "Energy Benchmarking Report Slovenia," Presentation, International Benchmarking Conference, Bratislava, Slovak Republic, March 31. http://www.opetchp.net/download/wp5/WP5_T5_benchmarking_conference_JSI_Slovenia.pdf

21) Martin, N., E. Worrell, M. Ruth, L. Price, R.N. Elliott, A.M. Shipley, and J. Thorne, 2000, Emerging Energy-Efficient Industrial Technologies, Lawrence Berkeley National Laboratory, LBNL-46990. http://eetd.lbl.gov/ea/ies/iespubs/46990.pdf

22) Mermelstein, N.H., 1998, "Microwave and Radiofrequency Drying," Food Technology, 52(11), pp. 84-85.

23) Orsat, V., and G.S. Vijaya Raghavan, 2005, "Radio Frequency Processing," in D.W. Sun (Ed.), Emerging Technologies for Food Processing, Elsevier Academic Press, Amsterdam.

24) Perez, A. and S. Pollack, 2002, Fruit and Tree Nuts Outlook, Economic Research Service, United States Department of Agriculture, Washington, D.C. Report # FTS-296. http://www.ers.usda.gov/publications/fts/jan02/fts296.pdf

25) Radio Frequency Company, 2006, online excerpt from Malovany, D., "Pepperidge Farm Tour - Still the leader," Snack Food and Wholesale Bakery Magazine. http://www.radiofrequency.com/pressreleases/pr_13.html

26) Rumsey, T.R., 1986, "Energy Use in Food Blanching," in Singh, R.P. (Ed.), Energy in Food Processing, Elsevier, Amsterdam.

27) Singh, R.P., 1986, "Energy Accounting of Food Processing Operations," in Singh, R.P. (Ed.), Energy in Food Processing, Elsevier, Amsterdam.

28) Spreen, T.H., W. Fernandes, C. Moreira, and R.P. Muraro, 2001, An Economic Evaluation of Hamlin Versus Valencia Orange Production in Florida," Department of Food and Resource Economics, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida. Report FE 300.

29) Southern California Edison (SCE), 1995, Customer Technology Application Center Profile #84, Rosemead, California, www.bpa.gov/energy/n/reports/Results_Center/pdf/84.pdf.

30) Toepfl, S., V. Heinz, and D. Knorr, 2005, "Overview of Pulsed Electric Field Processing for Food," in D.W. Sun (Ed.), Emerging Technologies for Food Processing, Elsevier Academic Press, Amsterdam.

31) United States Census Bureau, 2006, 2002 Economic Census, Geographic Area Series, Washington, D.C.

32) United States Climate Technology Cooperation, 2005, Greenhouse Gas Equivalencies Calculator. http://www.usctcgateway.net/tool/

33) United States Department of Agriculture, Economic Research Service, 2005, Food Consumption (Per Capita) Data System, Washington, D.C. http://www.ers.usda.gov/data/FoodConsumption/

34) United States Department of Agriculture, Economic Research Service, 2003, “Food Manufacturing Productivity and its Implications,” Washington, D.C., TB-1905

35) United States Department of Agriculture, Economic Research Service, 2005, Dairy: Background

36) United States Department of Agriculture, Economic Research Service, 2005b, Dairy Yearbook 2004, Washington, D.C. http://www.ers.usda.gov/Data/sdp/view.asp?f=livestock/89032/&arc=C

37) United States Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau, Statistics for Industry Groups and Industries: 2004, December 2005, Washington, D.C.

38) United States Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau, Value of Product Shipments: 2004, December 2005, Washington, D.C.

39) United States Department of Energy, Energy Information Administration, 2005a, 1990 - 2004 Net Generation by State by Type of Producer by Energy Source (EIA-906), Washington, D.C. http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html

40) United States Department of Energy, Energy Information Administration, 2005b, 1990-2004 U.S. Electric Power Industry Estimated Emissions by State (EIA-767 and EIA-906), Washington, D.C. http://www.eia.doe.gov/cneaf/electricity/epa/epa_sprdshts.html

41) U.S. Department of Energy, Energy Information Administration, 2005c, 2004 Consumption of Fossil Fuels for Electricity Generation by Type of Power Producer, Washington, D.C. http://www.eia.doe.gov/cneaf/electricity/epa/epat4p1.html

42) United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, Summary of ITP Program Impacts, January 2005, Washington, D.C., www.pnl.gov/impacts/

43) United States Department of Energy, Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program, "Evaporator Fan Controller for Medium Temperature Walk-in Refrigerators", Success Story, October 2001, Washington, D.C., http://www.e3energy.org/schrum.pdf

44) United States Department of Energy, 2003, Evaporator Fan Controller for Medium-Temperature Walk-In Refrigerators, Office of Energy Efficiency and Renewable Energy, Washington, D.C. http://www.eere.energy.gov/inventions/pdfs/artinc.pdf

45) United States Department of Labor, Bureau of Labor Statistics, "Consumer Expenditures in 2003," Report 986, June 2005, Washington D.C.

46) United States Environmental Protection Agency, 2002, U.S. Greenhouse Gas Emissions In Brief, Washington, D.C. Report # EPA 430-F-02-008

47) United States Environmental Protection Agency, 2004, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002, Annex 2, Table 2-1, Washington, D.C.

48) Unterseher, R., L. Barnett, N. Moore, and R. Conger, 2000, The Turbo-Flo Blancher/Cooker Saves Energy and Improves Product Quality, Centre for Analysis and Dissemination of Demonstrated Energy Technologies, Newsletter No. 3. http://www.caddet.org/public/uploads/pdfs/newsletter/003_05.pdf

49) Vega-Mercado, H., M. M. Gongora-Nieto, and G.V. Barbosa-Canovas, 2001, "Advances in Dehydration of Foods," Journal of Food Engineering, 49(2001), pp. 271-289.

50) Wilson, B., 2001, "Combining Radio Frequency and Conventional Methods," Process Heating, March 5th. http://www.process-heating.com/